Unified Parameterization of the Marine Boundary Layer

PI Joao Teixeira
Jet Propulsion Laboratory, California Institute of Technology, MS 169-237, 4800 Oak Grove Drive, Pasadena, CA, 91109
phone: (818) 354-2762 email: teixeira@jpl.nasa.gov

Collaborator James D. Doyle
Marine Meteorology Division, Naval Research Laboratory, Monterey, CA, 93943-5502
phone: (831) 656-4716 email: james.doyle@nrlmry.navy.mil

Award Number: N0001408IP20064

LONG-TERM GOALS

The long term goals of this effort are (i) the development of a unified parameterization for the marine boundary layer; (ii) the implementation of this new parameterization in the US Navy COAMPS mesoscale model; and (iii) the transition of this new version of the COAMPS model into operations at Fleet Numerical Meteorology and Oceanography Center (FNMOC).

OBJECTIVES

The objectives of this project are: i) to develop a unified parameterization for the Marine Boundary Layer (MBL) and ii) to implement and test this parameterization in the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS®[1]).

APPROACH

This unified boundary layer parameterization will be based on two main components: (i) the Eddy-Diffusivity Mass-Flux (EDMF) parameterization of boundary layer mixing; and (ii) the Probability Density Function (PDF) cloud parameterization.

Together these two concepts allow for the unification of MBL parameterization in one single scheme. They also allow for the development of physical parameterizations that lead to a resolution-dependent MBL parameterization that would adjust itself to the horizontal grid resolution.

Key personnel:

J. Teixeira (JPL/Caltech) uses his expertise in cloud and boundary layer parameterizations to guide the development and implementation of the EDMF/PDF parameterization.

---

[1] COAMPS® is a trademark of the Naval Research Laboratory.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
2010		**00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE **Unified Parameterization of the Marine Boundary Layer**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **California Institute of Technology,Jet Propulsion Laboratory,MS 169-237, 4800 Oak Grove Drive,Pasadena,CA,91109**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**20**	

J. Doyle (NRL) uses his expertise in mesoscale modeling to assist with the investigations related to COAMPS within the context of his existing ONR project.

M. Witek (Caltech Postdoc) performs the development and implementation of the EDMF parameterization in the COAMPS model.

G. Matheou (JPL/Caltech) develops the Large-Eddy Simulation (LES) model and performs simulations for marine boundary layer cases.

WORK COMPLETED

Tasks completed:

- Performed EDMF single-column studies with decomposition between large scales (parameterized by the MF term) and small scales (ED) for a variety of convective boundary layer cases including marine cases such as stratocumulus and cumulus-topped boundary layers;
- Implemented and tested new EDMF parameterization in COAMPS model.
- Tested new EDMF approaches for the parameterization of TKE transport term.
- Utilized Large-Eddy Simulation (LES) model to simulate cumulus-topped boundary layers and to calibrate EDMF parameterization implemented in COAMPS

RESULTS

In previous reports we have described in detail the new EDMF parameterization and its implementation in COAMPS. For this fiscal year, the description of achievements includes:

1. Summary of an integrated TKE-based EDMF boundary layer closure for the convective boundary layer
2. An EDMF approach to the vertical transport of TKE in convective boundary layers
3. EDMF in COAMPS – extension to shallow cumulus parameterization.

The first category concerns the EDMF parameterization implementation and testing in a single column model. This study was performed in order to improve the formulation of the EDMF approach, extend it by the use of TKE for the representation of key model parameters, as well as to assess model sensitivity to key EDMF parameters. The second point addresses the issue of an appropriate TKE simulation in a 1-D model, by the incorporation of MF vertical transport of TKE. The findings described in point 1 as well as several other studies showed that the commonly employed ED approach to vertical transport of TKE lacks sufficient accuracy, impairing the consistency of the EDMF framework. The proposed new method is designed to improve the TKE prediction in a simplified 1-D setup but also in the context of COAMPS simulations. The last point incorporates all technical issues related to the implementation of EDMF in the new version of the COAMPS model. The first subject is fully described in Witek et al. (J. Atmos. Sci., 2010, in revision). Here, only a short summary is provided. The second subject is more extensively presented in the following paragraphs. This topic will be submitted for publication shortly. The third subject is only briefly analyzed here, since the COAMPS 4 implementation and extension to shallow cumulus parameterization is in progress.

An integrated TKE-based eddy-diffusivity/mass-flux boundary layer closure for the dry convective boundary layer

This study presents a new approach to the eddy-diffusivity/mass-flux (EDMF) framework for the modeling of convective boundary layers. At the root of EDMF lays a decomposition of turbulent transport mechanisms into strong ascending updrafts and smaller-scale turbulent motions. The turbulent fluxes can be therefore described using two conventional approaches: mass-flux (MF) for the organized thermals and eddy-diffusivity (ED) for the remaining turbulent field. Since the intensities of both MF and ED transports depend on the kinetic energy of the turbulent motions, it seems reasonable to formulate an EDMF framework based on turbulent kinetic energy (TKE). Such approach allows for more physical and less arbitrary formulations of parameters in the model. In this study the EDMF–TKE coupling is achieved through the use of (i) a new parameterization for the lateral entrainment coefficient ε and (ii) the MF contribution to the buoyancy source of TKE. Some other important features of the EDMF parameterization presented here include a revised mixing length formulation and Monin–Obukhov stability scaling for the surface layer. The scheme is implemented in a one-dimensional (1D) model. Several cases of dry convective boundary layers (CBL) with different surface sensible heat fluxes in the free-convection limit are investigated. Results are compared to large-eddy simulations (LES). Good agreement between LES and 1D model is achieved with respect to mean profiles, boundary layer evolution, and updraft characteristics. Some disagreements between the models are found to most likely relate to deficiencies in the TKE simulation in the 1D model. Comparison with other previously established ε parameterizations shows that the new TKE based formulation leads to equally accurate, and in many respects better simulation of the CBL. The encouraging results obtained with the proposed EDMF framework indicate that full integration of EDMF with higher order closures is possible and can further improve boundary layer simulations.

An Eddy-diffusivity/mass-flux approach to the vertical transports of turbulent kinetic energy in convective boundary layers

In this study a new approach to the vertical transport of the turbulent kinetic energy (TKE) is proposed. The principal idea behind the new parameterization is that organized updrafts or convective plumes play an important role in transferring TKE vertically within convectively driven boundary layers. The parameterization is derived by applying an updraft-environment decomposition to the vertical velocity triple correlation term in the TKE prognostic equation. The additional mass-flux (MF) term that results from this decomposition closely resembles the features of the TKE transport diagnosed from large-eddy simulations (LES), and accounts for 97% of the LES diagnosed transport when the updraft fraction is set to 0.13. Another advantage of the MF term is that it is a function of the updraft vertical velocity, and can be readily calculated using already existing parameterization. The new MF approach, combined with several eddy-diffusivity formulations, is implemented into a simplified 1D TKE prognostic model. The 1D model results, compared against LES simulations of dry convective boundary layers, show substantial improvement in representing the vertical structure of TKE. The new combined eddy-diffusivity/mass-flux parameterization, as well as the MF term alone, surpasses in accuracy the eddy-diffusivity parameterizations. The proposed TKE transport parameterization shows large potential of improving TKE simulations in mesoscale and global circulation models.

Introduction

Vertical turbulent fluxes of heat, humidity and momentum are key elements in numerical models of planetary boundary layers. These fluxes are usually approximated using an eddy-diffusivity (ED)

approach, where vertical fluxes are assumed to be proportional to the local gradient of the mean profiles. A proportionality function, referred to as a *K* or ED diffusion coefficient, is parameterized using formulations of various levels of complexity and physical sophistication (Holt and Raman 1988, Stull 1988, Wyngaard 1992). A well established consensus is that higher order closures, like those based on the turbulent kinetic energy (TKE), are more accurate in simulating various boundary layer scenarios than less sophisticated first-order closures (e.g. Mellor and Yamada, 1982; Holt and Raman, 1988; Alapaty et al. 1997; Lenderink and Holtslag 2000; Wensong and Taylor 2003; Cuxart et al. 2006). For that reason they are becoming more popular in mesoscale and global atmospheric models. The success of such higher order schemes, however, relays directly on the accuracy of TKE simulations.

The ED approach has been fairly successful in a number of atmospheric conditions. It has, however, some structural limitations that hamper its performance in convective boundary layers (CBL) or in neutrally stratified conditions, where the gradients of average profiles are close to zero. To address these issues an eddy-diffusivity/mass-flux (EDMF) framework has been developed (Siebesma and Teixeira, 2000; Siebesma et al. 2007). It incorporates a nonlocal vertical turbulent transport of scalar variables, carried out by strong thermals or convective plumes, always observed in CBLs. Therefore, the EDMF schemes inherit all benefits of the ED approach and further extend it with the nonlocal transport contribution that improves simulations of neutral and slightly stable atmospheric conditions. The addition of the mass-flux (MF) term has enabled a better coupling between dry convection and clouds and has improved simulations of potential temperature, humidity and pollutant concentration (Soares et al. 2004; Angevine 2005; Hurley 2007; Siebesma et al. 2007; Soares et al. 2007; Neggers et al. 2009; Neggers 2009).

Some of the EDMF schemes developed so far use a TKE closure to parameterize the ED coefficient (Soares et al. 2004; Angevine 2005). A recent study by Witek et al. (2010) couples both ED and MF with a TKE closure. However, all these parameterizations use only an ED approach to represent the vertical transport of TKE. This can lead to errors in simulating the TKE structure, especially in the convectively driven boundary layers. The presence of strong, organized updrafts with high vertical velocities suggests a highly nonlocal redistribution of TKE. Updrafts themselves constitute large part of TKE and they often extend through the whole depth of the CBL. Witek et al. (2010) argue that the ED transport of TKE leads to TKE underestimation in the upper parts of the CBL. Also, the relatively constant values of TKE in the mixed layer, as suggested by large-eddy simulation (LES) results, cannot be accurately resolved using only an ED parameterization. These facts point to the need for a nonlocal TKE transport parameterization, which could be employed in a similar fashion to that of the EDMF framework. In the present study we address this issue and propose a MF parameterization of vertical transport of TKE that, along with ED, forms an EDMF framework for TKE.

The paper is organized as follows. Section 2 describes LES results of the dry convective boundary layer cases investigated here. The EDMF parameterization for TKE vertical transport is introduced in section 3. Additionally, some features of the parameterization are analyzed based on LES data. In section 4 a simplified one-dimensional (1D) model for TKE prognostic equation is developed. Results of this model, compared against LES, are used to verify performance of the new parameterization. Some conclusions and perspective for the EDMF formulation follow in section 5.

LES simulations

The LES code used in this study is a modified version of UCLA-LES (Stevens et al. 2005; Stevens and Seifert 2007). The Favre-filtered (density-weighted) Navier–Stokes equations, written in the anelastic form (Ogura and Phillips 1962; Vallis 2006), are numerically integrated. The constant-coefficient Smagorinsky LES–SGS model (Smagorinsky 1963; Lesieur and Metais 1996) with Lilly's (1962) stability correction is used for turbulent momentum, temperature and humidity transport. The Smagorinsky coefficient is set to $C_S = 0.23$. Scalar eddy-diffusivities are assumed proportional to the momentum eddy-diffusivity with a turbulent Prandtl number, $\mathrm{Pr}_t = 1/3$. The discrete equations are integrated on a staggered mesh using fully conservative second-order accurate centered differences (Harlow and Welch 1962; Morinishi et al. 1998). Time integration is accomplished by a low-storage third order Runge–Kutta method (Spalart et al. 1991). The time step is variable and is adjusted to maintain a constant CFL number of 0.3.

A series of four LES runs are performed with various surface sensible heat fluxes $\overline{w'\theta'}_s$ equal 0.03, 0.06, 0.09 and 0.12 K m/s. Initial conditions are based on the profiles established by Niewstadt et al. (1992), which can be summarized by

$$\theta = 300 \text{ K}, \ \partial q/\partial z = -3.7\times10^{-4} \text{ km}^{-1}, \ \ 0 < z < 1350 \text{ m},$$
$$\partial\theta/\partial z = 2 \text{ K km}^{-1}, \ \partial q/\partial z = -9.4\times10^{-4} \text{ km}^{-1}, \ \ z > 1350 \text{ m}.$$

The surface humidity flux is kept constant $\overline{w'q'}_s = 2.5\times10^{-5}$ m/s. The surface pressure is set to $p_s = 1000$ hPa. The free convection conditions are assured by setting initial mean wind speed profile as $(u_0, v_0) = (0.01, 0)$ m/s. The LES simulations are performed on a domain with a uniform grid spacing of $\Delta x = \Delta y = \Delta z = 20$ m. The domain size is 8 × 8 km in the horizontal, whereas in the vertical 4 and 5 km are used for the simulations with surface heat fluxes of (0.03, 0.06) and (0.09, 0.12) K ms^{-1}, respectively. Model results are output every 10 minutes.

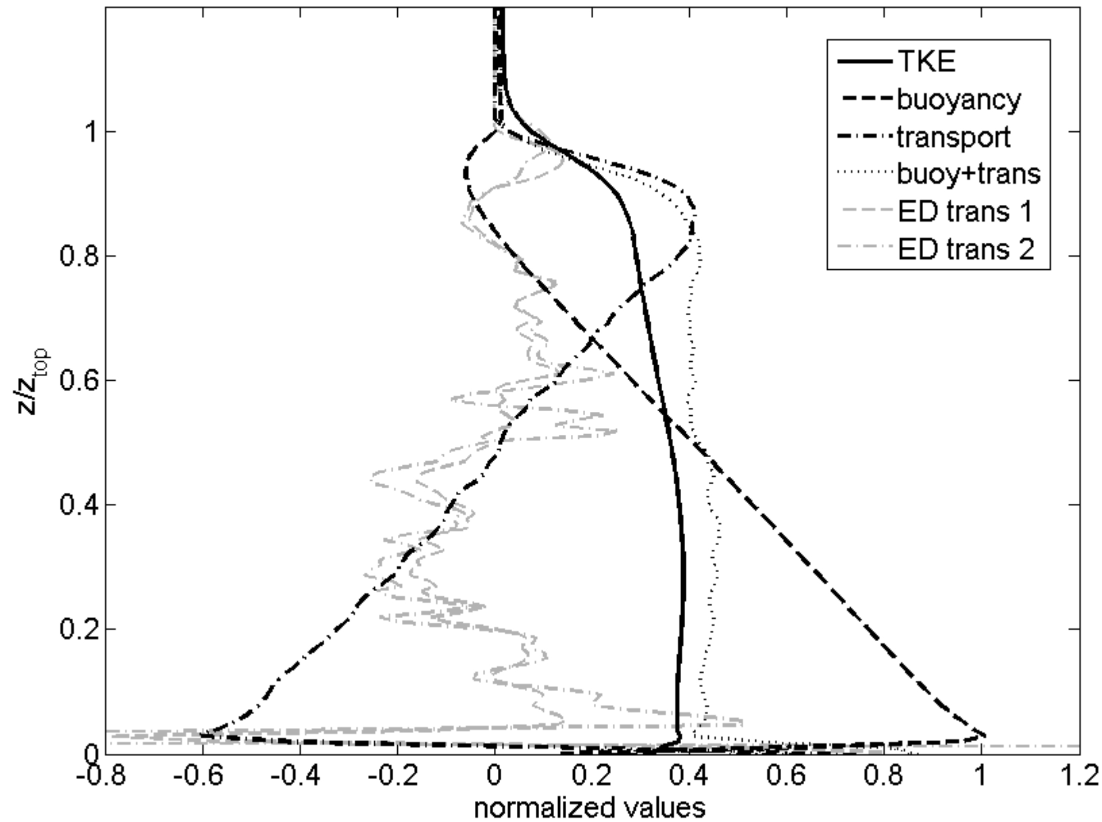

Figure 1 Normalized TKE and TKE budget terms, averaged over LES results from 2-8h. The grey dashed (ED trans 1) and dashdot (ED trans 2) lines represent projected eddy-diffusivity transport terms obtained using the TKE profile and two different K-coefficient parameterizations described in section 3

Fig. 1 shows normalized TKE and TKE budget terms (solid, dashed and dashdot black lines) obtained from the four LES simulations and averaged between 2nd and 8th simulation hour. The buoyancy source term $\overline{w'\theta_v'}\,g/\overline{\theta}_v$ and the transport term $-\partial\overline{w'e'}/\partial z - \partial\overline{w'p'}/\partial z$ are derived from the LES output. Normalization of TKE is obtained by dividing by w_*^2, where $w_* = \left(g/T_v\,\overline{w'\theta_v}\right)_s^{1/3}$ is the convective velocity scale. The buoyancy and transport terms are normalized using z_{top}/w_*^3, where z_{top} is the boundary layer height defined as the level of the maximum gradient of potential temperature (e.g. Siebesma et al., 2007).

The normalized TKE budget profiles exhibit a typical structure found in the CBL (e.g. Nieuwstadt et al 1992). TKE is driven by the surface heating and resulting buoyant instabilities, and transported upwards by vertical velocity fluctuations. The turbulent transport is negative in the lower half of the CBL, being a local loss term, and positive in the upper half, contributing to the local TKE production. Integrated over the whole CBL, becomes zero. The sum of the buoyancy and transport terms, shown in Fig. 1 as the black dotted line, is almost constant within the CBL and decreases to zero at the inversion. The profile of TKE is also relatively constant with height, indicating that the TKE dissipation (not shown) scales directly with TKE. This suggests the form of a dissipation length scale, presented in section 4.

The average TKE profile from Fig. 1 can be used to assess the TKE transport as projected by different ED parameterizations, according to the formula $\partial/\partial z\left(K\,\partial e/\partial z\right)$, where K is an ED coefficient. In order to estimate the ED transport terms, two different K parameterizations (K_1 and K_3 in Table 1), combined with the conditions at the end of the LES simulation with surface flux 0.06 Km/s, are used. Results of the projected ED transports are plotted in Fig. 1 as the grey dashed and dashdot lines. Such straightforward approach, even though highly simplified, reveals substantial difficulties of the ED parameterization to represent the TKE transport in CBLs. In particular, our simple test suggests that the TKE structure such as that presented in Fig. 1 is virtually impossible to achieve using a classical ED formulation. Alternative approaches are required to address this problem. One such idea, that combines the ED and MF concepts, is introduced in the following section.

Basic concept of the eddy-diffusivity/mass-flux transport of TKE

The TKE prognostic equation can be written as (e.g. Stull, 1988)

$$\frac{\partial e}{\partial t}=\frac{g}{\overline{\theta_v}}\overline{w'\theta_v'}-\frac{\partial\overline{w'e}}{\partial z}-\frac{1}{\rho}\frac{\partial\overline{w'p'}}{\partial z}-\varepsilon-\overline{u'w'}\frac{\partial\overline{u}}{\partial z}-\overline{v'w'}\frac{\partial\overline{v}}{\partial z}, \tag{1}$$

where the first term on the RHS represents the buoyancy production, the second and third term represent the transport, ε is the TKE dissipation and the last two elements represent the shear production. The vertical transport by turbulent motions can be further split into

$$\frac{\partial\overline{w'e}}{\partial z}=\frac{1}{2}\left(\frac{\partial\overline{w'u'^2}}{\partial z}+\frac{\partial\overline{w'v'^2}}{\partial z}+\frac{\partial\overline{w'w'^2}}{\partial z}\right). \tag{2}$$

In CBLs the vertical motions can have very large velocities and can be organized into localized ascending plumes. This suggests that an updraft-environment decomposition can be applied to the vertical velocity triple correlations. A similar approach has been already successfully applied to the vertical fluxes of scalar variables in the EDMF parameterizations. Following Randall et al. (1992) and Siebesma et al. (2007) gives

$$\overline{w'^3}\cong\overline{w'^3}^{e}+\sigma(1-\sigma)(1-2\sigma)(w_u-w_e)^3, \tag{3}$$

where the sub- and superscripts u and e refer to the updrafts and the complementary environmental part and σ is the fractional area occupied by updrafts. The global area average satisfies $\overline{w}=\sigma w_u+(1-\sigma)w_e=0$. Without losing much generality it can be written that

$$\overline{w'e}\cong\overline{w'e}^{e}+\frac{1}{2}\sigma\frac{1-2\sigma}{(1-\sigma)^2}w_u^3. \tag{4}$$

Based on Eq. 4, the final form of a new EDMF parameterization of the turbulent transport of TKE can be formulated

$$\frac{\partial \overline{w'e}}{\partial z}+\frac{1}{\rho}\frac{\partial \overline{w'p'}}{\partial z}\cong\frac{\partial}{\partial z}\left(-K\frac{\partial e}{\partial z}\right)+\frac{3}{2}\sigma w_u^2\frac{\partial w_u}{\partial z}\left(1-\frac{\sigma^2}{(1-\sigma)^2}\right), \tag{5}$$

$$\text{TKE transport} \quad \cong \quad \text{ED term} \quad + \quad \text{MF term}$$

where K is the diffusion coefficient for TKE.

The vertical turbulent transport of TKE is decomposed into the ED and MF term. The MF term becomes zero when σ approaches 0.5. This can be interpreted as a situation when there is no clear distinction between updrafts and complementary environmental part as in a weak mixing scenario or when turbulence is being mainly generated by horizontal shear. In such cases the updraft-environment decomposition loses its foundation. In convectively driven boundary layers, on the other hand, σ has been traditionally chosen to be about 0.1. Such value is often assumed in EDMF parameterizations for scalar fluxes (Soares et al. 2004; Siebesma et al. 2007; Neggers et al. 2009). Small σ implies that the expression in the parenthesis in the MF term can be approximated with 1. An important advantage of the MF term is that it only depends on the updraft velocity, which can be readily derived from the existing parameterizations. The updraft velocity is already a key component of many EDMF parameterizations, where it is derived using modified versions of the Simpson and Wigget's (1969) equation. Those parameterizations are usually sufficiently accurate, as indicated by various comparisons against w_u derived from LES results (e.g. Soares et al. 2004; Siebesma et al. 2007; Neggers et al. 2009).

Fig. 2 presents the MF component from Eq. 5, normalized and averaged, as diagnosed from LES results, together with the transport calculated from LES. The updraft fraction is set to 0.13 for the reasons described later in this section. Additionally, the MF term obtained with the updraft fraction 0.1 is presented with the dotted line. The MF term follows the LES transport remarkably well, having a similar vertical structure and a comparable magnitude to the LES values. The similarities are even more pronounced when compared with the projected ED transport presented in Fig. 1. A more detail evaluation shows some minor disagreements; in particular the MF term slightly overestimates TKE removal from the surface layer and underestimates the transport close to the inversion. It also becomes a TKE source term above around 0.4 of the CBL height, a bit lower than LES. When integrated over the whole CBL the MF term vanishes, preserving an important attribute of the actual TKE vertical transport. When an updraft fraction is lowered to a typically used 0.1 value the results of the MF parameterization remain quite similar, confirming that the MF term produces stable outcomes for the range of σ values commonly used by investigators. The resemblance of the MF term to the LES calculated transport suggests its potential application in numerical models as a representation of turbulent transport of TKE. The MF term can be used exclusively, or in combination with ED, forming an EDMF framework for TKE modeling.

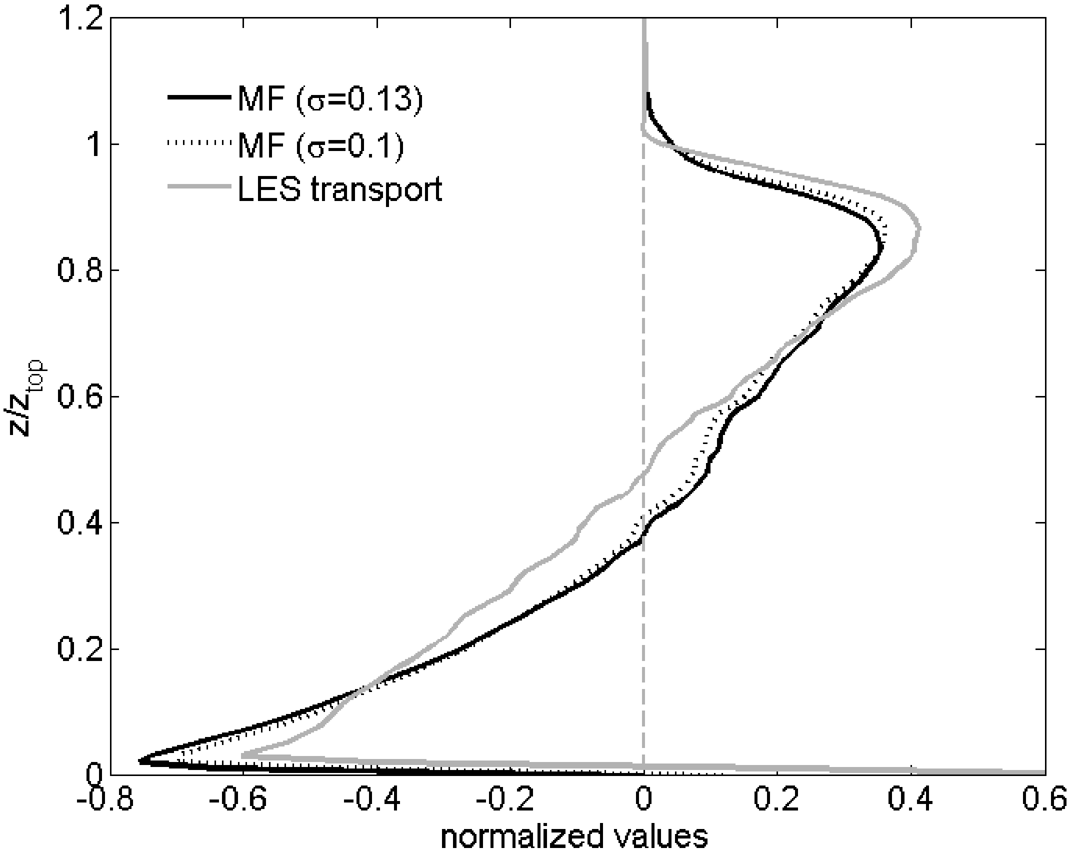

Figure 2 Normalized and averaged MF transport of TKE calculated from Eq. 5 with σ=0.13 (black line) and σ=0.1 (dotted line); grey line – LES transport term.

LES results described in the previous section are used to investigate an optimal updraft fraction for which the difference between the LES derived transport and the parameterized MF transport (Eq. 5) is the smallest. The difference in absolute values is investigated. Fig. 3 shows those minimal differences (represented as the fraction of the LES transport) and the corresponding updraft fractions for each LES model output. The crossings of the dashed lines indicate mean values. On average the MF term accounts for 97% of LES transport, with the mean updraft fraction ~0.13. Individual results vary between 80–110% and σ range between 0.1–0.15. A simple MF parameterization is therefore able to fully resolve the vertical turbulent transport of TKE.

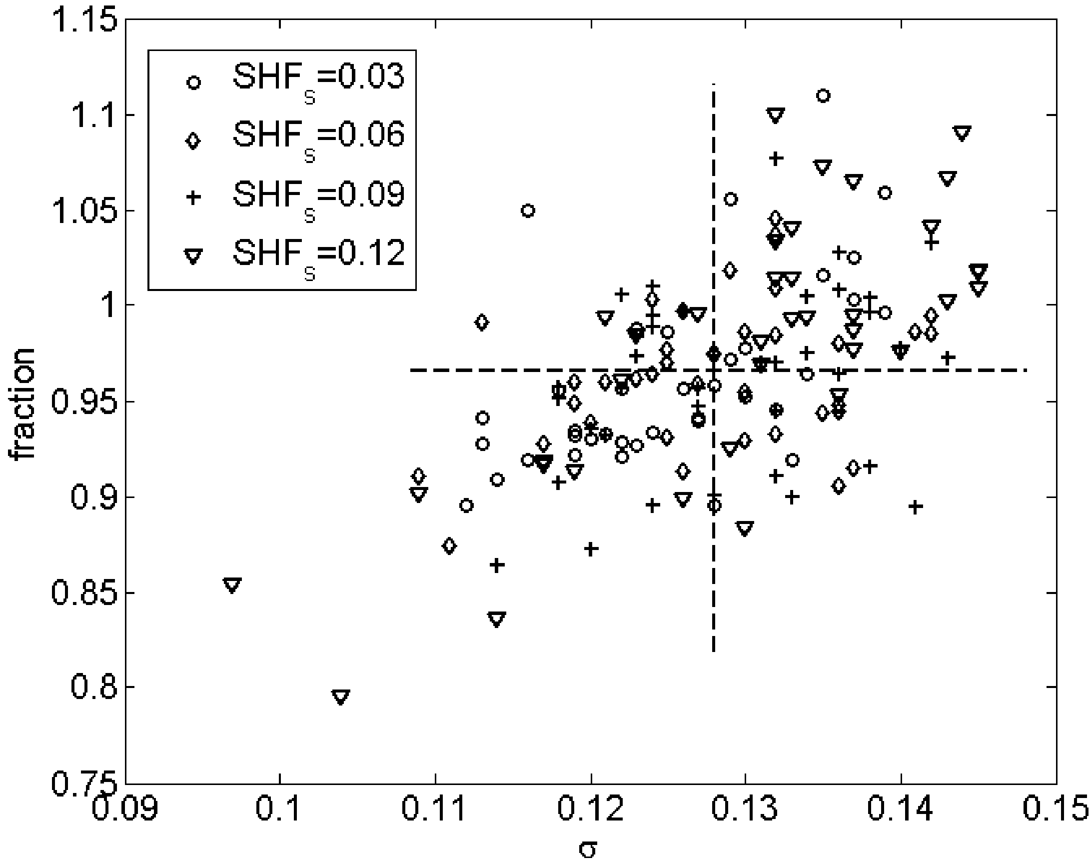

Figure 3 Maximum fraction of LES transport that can be obtained with the MF parameterization (see Eq. 5) as a function of the updraft area σ for which this maximum transport is achieved. The crossing dashed lines mark the average values.

1D model results

The concept of an EDMF transport of TKE introduced in the previous section is evaluated here using a simplified 1D TKE model. The modified TKE prognostic equation has the form

$$\frac{\partial e}{\partial t} = \frac{g}{\overline{\theta_v}} \overline{w'\theta_v'} - \varepsilon - \frac{\partial}{\partial z}\left(-K\frac{\partial e}{\partial z}\right) - \alpha\sigma w_u^2 \frac{\partial w_u}{\partial z}, \tag{5}$$

where $\alpha = 1.5$ is a scaling coefficient and $\sigma = 0.13$. The last two terms represent the ED transport and the MF transport, respectively. An important assumption in the model is that the buoyancy source term is being prescribed using the normalized profile presented in Fig. 1. The updraft vertical velocity, as well as other variables important for the integration, is also prescribed using normalized profiles obtained from LES. These steps allow isolating the TKE prognostic equation and concentrate on the performance of the transport terms, without solving prognostic equations for temperature and humidity. The initial state and the boundary conditions are based on the LES results from the simulation with surface heat flux 0.06 Km/s. The boundary layer height z_{top} and the vertical velocity scale w_* from the same LES simulation are used to convert the normalized profiles to actual buoyancy

and $\overline{w}_u$ values. The 1D model simulations span between 2nd and 8th hour of the LES simulation and results after 6-hour integration are analyzed. Eq. 5 is solved on a regular 10m grid; time step is set to 60s.

Variables that are derived based on model integrated TKE values include the TKE viscous dissipation ε and the *K* diffusion coefficient. The dissipation is parameterized according to

$$\varepsilon = c_\varepsilon \frac{e^{3/2}}{l_\varepsilon}, \tag{6}$$

where c_ε is a coefficient that can vary in time and $l_\varepsilon = \tau\sqrt{e} = 0.5\, z_{top} / w_* \sqrt{e}$ is a dissipation length scale (Teixeira and Chainet 2004; Witek et al. 2010). Note that no additional scaling is applied to the dissipation length scale, as previously suggested by the LES results presented in Fig. 1. The coefficient c_ε scales uniformly TKE dissipation and is adjusted at each time step during simulations in a way such that the vertically integrated TKE is equal to that derived from the LES data. Such procedure allows for more oriented investigation of transport processes, keeping limits to the total turbulence intensity. In practice, the value of c_ε, after initial oscillations related to a fixed choice at the initialization (set to 0.6), remain relatively stable throughout the simulations (results not shown). Those c_ε values, however, vary slightly between simulations depending on the choice of *K* coefficient parameterization.

In this study three different ED coefficient parameterizations found in the literature are used to investigate TKE transport in 1D model simulations. An overview of these formulations is presented in Table 1; a detailed description can be found in Appendix A. In general, they were originally formulated as parameterizations of the transfer coefficients of heat, rather than momentum. In our opinion this is an acceptable approach, given the lack of substantial differentiation between them. Similar, or varying by a factor of $\mathrm{Pr} \cong 0.75$ (Wensong and Taylor 2003), where Pr is the turbulent Prandtl number, *K* parameterizations are often employed by investigations for heat, momentum, and TKE diffusion coefficients.

In short, K_1 uses a prescribed profile, whereas K_2 and K_3 are both based on TKE but employ different mixing length formulations and different surface layer and static stability scaling. The static stability scaling in both cases depends mainly on the Brunt-Väisälä frequency (for definition see Appendix A), which is diagnosed at each time step from the LES derived temperature and humidity profiles. Stability corrections affect the whole K_2 profile, whereas in the case of K_3 they only influence the profile in the upper part of the CBL. Examples of the three *K* parameterizations are presented in Fig. 4b. Strong fluctuations in K_3, and some sharper gradients in K_2, are consequences of the static stability scaling and computation of the Brunt-Väisälä frequency. Under a close to neutral θ profile, as depicted in Fig. 4a, the Brunt-Väisälä frequency exhibits very small oscillations around zero. The S_h function proves to be sensitive to those fluctuations, amplifying them and causing substantial variations in the K_2 profile. In Bretherton and Park (2009) this feature is not observed, mostly because their temperature profiles are always slightly unstable. They use the ED approach to represent turbulent transport of heat, which cannot accurately simulate neutral or slightly stable stratification. Also, K_2 drops substantially above around 800m and remains small up to the inversion.

Again, this is related to a slightly stable θ stratification simulated by LES which causes the scaling function S_h to be very small.

Table 1 Overview of the diffusion coefficient parameterizations used in this study. For a full description see Appendix A.

	K_1	K_2	K_3
Expression and references	$K_1 = K_1\left(\frac{z}{z_{top}}, u_*, w_*\right)$ Holtslag (1998)	$K_2 = l_2 S_h \sqrt{e}$ Bretherton and Park (2009)	$K_3 = a_3 l_3 \sqrt{e}$ Witek et al. (2010), Galperin et al. (1988)
Surface layer scaling	Prescribed	kz	$kz\, f(L)$
Static stability scaling	Prescribed	Embedded in S_h $S_h = S_h\left(N^2, l_2, e\right)$	Embedded in l_3 $l_3 = \min\left[l_3, g(N, e)\right]$

In Fig. 4c the TKE profiles (black lines) at 8th hour as simulated with the ED approach only using the three different *K* parameterizations are presented. The grey lines indicate the initial and the 8th hour LES results. All 1D model results are roughly agreeable with LES, but are clearly not capable of representing details of the TKE structure. The profiles are too shallow and TKE is highly overestimated in lower parts of the mixed layer. ED transport is not efficient enough to transfer TKE from lower elevations to higher parts of the CBL. For example, the profile obtained with K_2 is particularly shallow, which is related to very low K_2 values imposed by slightly stable θ profiles. Adjusting this static stability scaling in K_2 could improve its performance to make it more agreeable with the other two *K* parameterizations. However, our simulations suggest that much closer resemblance with the LES profile cannot be achieved using the ED approach only.

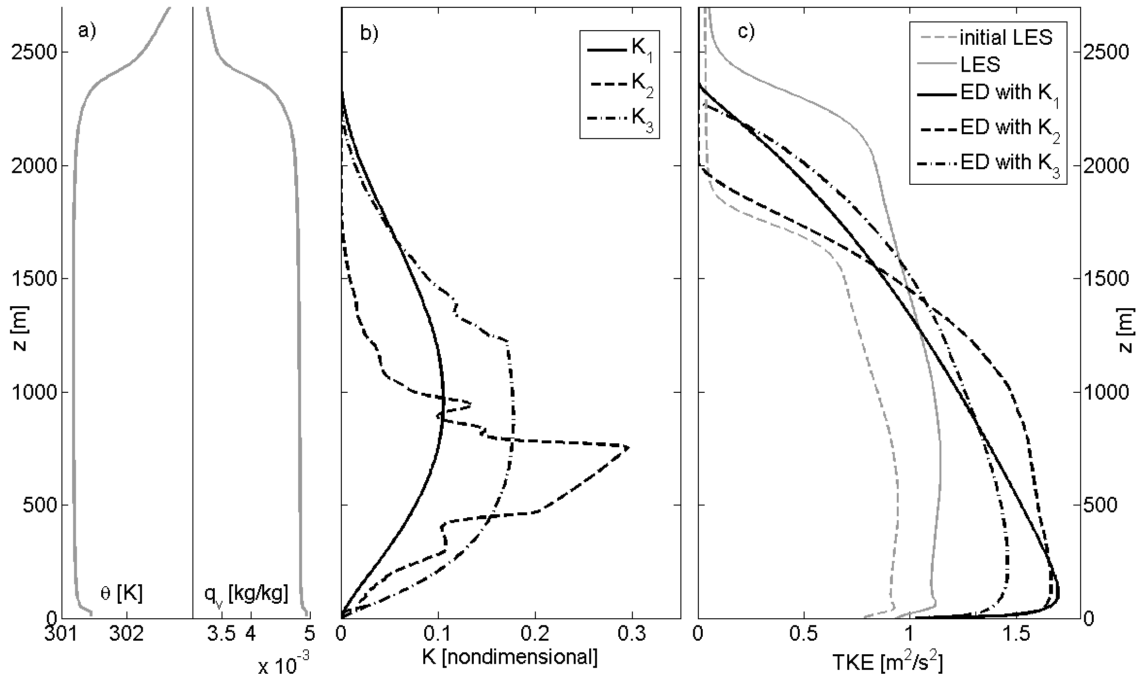

Figure 4 a) Potential temperature and humidity profiles at the end of the LES simulation with SHF_s=0.06 Km/s. b) Different K profiles at the end of 1D model simulations performed with the ED parameterization only. c) Final TKE profiles as simulated with various ED parameterizations (black lines); initial and final TKE profiles from the reference LES simulation (grey lines).

Fig. 5a shows results similar to these presented in Fig. 4c, but with the MF transport included in the simulations. σ is equal 0.13 and α coefficient is set to 1.5. A substantial improvement comparing to Fig. 4c is observed. All profiles are much deeper, reaching almost the same height as the LES result. The strong TKE overestimation in lower parts of the mixed layer is greatly reduced, and the LES and EDMF profiles are much closer to each other. In particular, the EDMF simulations are capable of reproducing relatively constant TKE values within the mixed layer, compared to the steadily decreasing profiles generated by the ED-only simulations. The addition of the MF term in the TKE transport parameterization substantially enhances the 1D model performance, giving very close agreement with the LES results.

In Fig. 5b the MF term is further investigated, whether it could partially or fully substitute the ED transport. The dotted line shows results of the simulation with the *K* coefficient set to zero. The MF transport performs very well by itself, surpassing in accuracy the ED parameterizations (see Fig. 4c). The transport overestimation in the surface layer evident in Fig. 2 leads to somehow reduced values of TKE compared to LES. Small wiggles are due to sensitivity of the w_u gradient computation. An addition of diffusive transport (dashed line in Fig. 5b), with *K* set to one-fourth of K_3, ensures a smooth profile and further improves the agreement with LES. Results are even better when *K* is increased to $0.75K_3$ (solid line in Fig. 5b), producing almost a perfect fit to the LES profile. These results indicate that the EDMF parameterization for TKE transport is very perspective to achieve more adequate and realistic simulations of TKE in mesoscale and global atmospheric models.

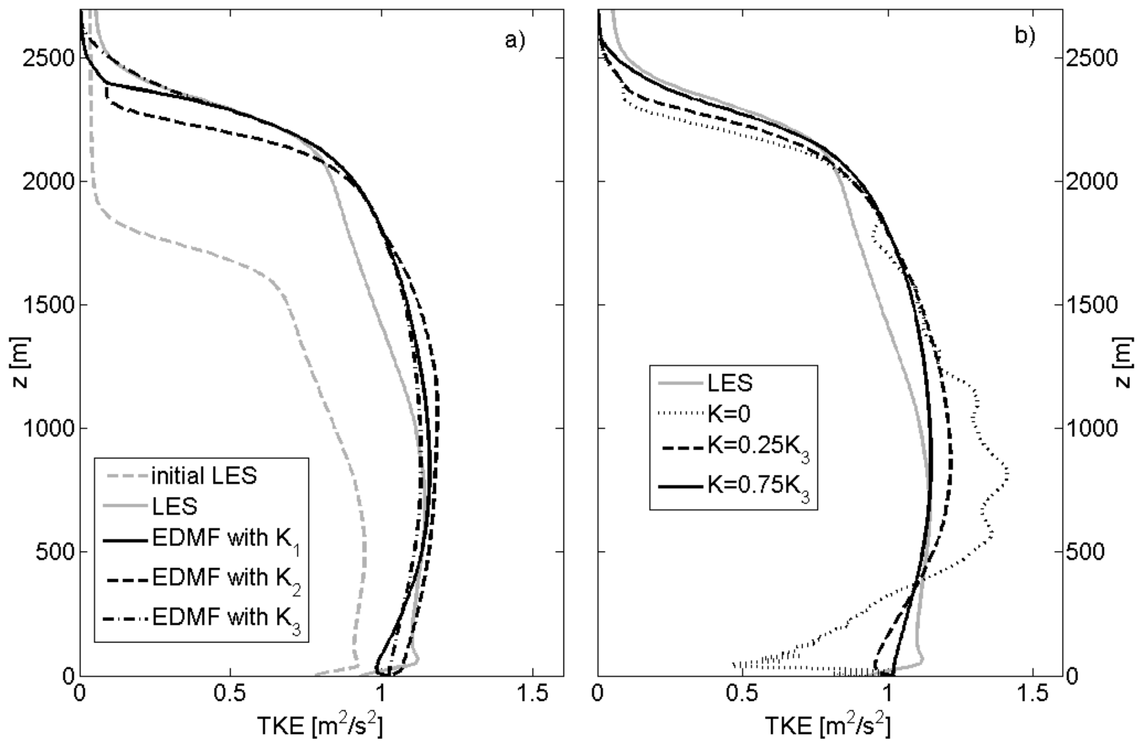

Figure 5 a) Final TKE profiles as simulated with various EDMF parameterizations (black lines); initial and final TKE profiles from the reference LES simulation (grey lines). b) Same as a) but with reduced K values.

DISCUSSION AND CONCLUSIONS

In this study a new approach to the vertical turbulent transport of TKE in convectively driven boundary layers is proposed. The main idea behind the new parameterization is that organized updrafts or convective plumes play an important role in transferring TKE vertically within the CBL. Convection tends to organize itself into localized buoyant updrafts which on average accelerate in the lower half of the CBL and slow down losing their momentum in the upper half. Visible manifestations of these updrafts are cumulus clouds often forming at the top of the CBL. During their life cycle the strongest updrafts interact with the turbulent field surrounding them. One possible interpretation for this interaction is that the updrafts acceleration is supported by the surrounding smaller scale turbulence, while when the updrafts are losing speed they deposit their energy to the surrounding flow making it more turbulent. The LES derived TKE transport term profile somehow confirms this conception: it has negative values where the updrafts accelerate and positive values where they decelerate.

This interpretation suggests that the strongest updrafts might be carrying most of the transport of TKE within the CBL. This is the key motivation for applying the updraft-environment decomposition to the vertical velocity triple correlation term in the TKE prognostic equation. The procedure creates an additional mass-flux term that can be used to parameterize the vertical transport of TKE. The LES results are used to evaluate the approach. The MF term, which is only a function of the updraft vertical velocity, closely resembles the features of the LES derived vertical transport of TKE. The MF term is,

on average, able to resolve 97% of the LES transport, with the mean updraft fraction equal 0.13. Individual results based on LES output vary between 80–110 %. By retaining the ED approach, an EDMF framework, similar to those used for the turbulent fluxes of heat and humidity, is formulated for the simulation of TKE.

The new EDMF parameterization is implemented in a simplified 1D model and its performance is tested against LES simulations. Several dry convective boundary layer cases are investigated. Three different *K* diffusion coefficient formulations are used to highlight differences between the ED-only and EDMF approaches. Results show a substantial improvement of 1D simulations when the MF term, together with the ED parameterizations, is employed. Even the MF term alone can produce better results than the ED parameterizations themselves. The new EDMF parameterization is able to represent extremely accurately the LES results even if the diffusion coefficient is greatly reduced. These results indicate the proposed EDMF parameterization has a large potential to increasing accuracy of TKE simulations in mesoscale and global atmospheric models.

Further work is however required to test usefulness of this new parameterization. The approach should be implemented and evaluated in a boundary layer model with a full set of prognostic equations for temperature and humidity, and not relying on LES derived profiles. Subsequent step would be to combine the EDMF transport of TKE with the existing EDMF formulations for temperature and humidity fluxes. This could lead to improvements in the updraft characteristics derivations based on TKE profiles. Another interesting research would be to test if the new MF parameterization could be used to imitate transport of TKE in the shallow cumulus and stratocumulus cases. Currently many models suffer from the insufficient accuracy in simulating TKE in the cloud layer, part of which could be due to problems with resolving the TKE transport.

Appendix A

A detailed description of the three different eddy-diffusivity parameterizations used in this study

Following Holtslag (1998)

$$K_1(z) = z_{top} w_* k \left[\left(\frac{u_*}{w_*} \right)^3 + 39k \frac{z}{z_{top}} \right]^{1/3} \frac{z}{z_{top}} \left(1 - \frac{z}{z_{top}} \right)^2 , \tag{7}$$

where $k = 0.4$ is the von Karman constant, $z_{top} = 0.4$ is the top of the boundary layer, u_* and w_* are the friction velocity and the convective velocity scale, respectively. u_* is derived according to the formula by Abella and McFarlane (1996), also described in Witek et al. (2010).
After Bretherton and Park (2009)

$$\begin{aligned} &K_2(z) = l_2 S_h \sqrt{e} , \\ &\left(\frac{1}{l_2} \right)^3 = \left(\frac{1}{kz} \right)^3 + \left(\frac{1}{l_\infty} \right)^3 , \\ &S_h = \frac{\alpha_1}{1 + \alpha_2 G_h}, \quad G_h = -\frac{N^2 l_2^2}{2e} , \end{aligned} \tag{8}$$

where $l_\infty = 0.17 z_{top}$, $\alpha_1 = 0.6986$, $\alpha_2 = -34.6764$, and $N^2 = g/\theta_v \, \partial\theta_v/\partial z$ is the squared moist Brunt-Väisälä frequency. G_h is additionally restricted at unstable stratifications by $G_h < 0.0233$.
Finally, following Witek et al. (2010)

$$
\begin{aligned}
&K_3(z) = l_3 \sqrt{e}\,, \\
&\frac{1}{l_3} = \frac{1}{l_a} + \frac{1}{l_b}, \\
&l_a = \tau\sqrt{e} = 0.5\frac{z_{top}}{w_*}\sqrt{e}\,, \quad l_b = kz\left(1 - 100\frac{z}{L}\right)^{0.2},
\end{aligned}
\tag{9}
$$

where L is the Monin-Obukhov length defined as $L = -u_*^3\theta_v \Big/ \left(kg\overline{w'\theta_v'}^s\right)$; g is the acceleration of gravity and $\overline{w'\theta_v'}^s$ is the buoyancy flux at the surface. L is derived simultaneously with u_* following the procedure by Abella and McFarlane (1996). l_a is the mixing length introduced by Teixeira and Cheinet (2004), and l_b follows the formulation by Nakanishi (2001). Additionally, l_3 is restricted at stable stratifications using the condition by Galperin et al. (1988)

$$
l_3 = \min\left(l_3, \frac{0.53\sqrt{e}}{N}\right). \tag{10}
$$

REFERENCES

Abdella, K. and N. A. McFarlane, 1996: Parameterization of the surface-layer exchange coefficients for atmospheric models. *Boundary-Layer Meteorol.*, **80**, 223–248.

Alapaty, K., J. E. Pleim, S. Raman, D. S. Niyogi, and D. W. Byun, 1997: Simulation of atmospheric boundary layer processes using local- and nonlocal-closure schemes. *J. Appl. Meteorol.*, **36** (3), 241–233.

Angevine, W., 2005: An integrated turbulence scheme for the boundary layer with shallow cumulus applied to pollutant transport. . *J. Appl. Meteorol.*, **44**, 1436–1452.

Betts, A. K., 1973: Non-precipitating cumulus convection and its parameterization. *Quart. J. Roy. Meteor. Soc.*, **99**, 178–196.

Bretherton, C. S. and S. Park, 2009: A new moist turbulence parameterization in the Community Atmosphere Model. *J. Climate,* **22**, 3422–3448.

Cuxart, J. and Coauthors, 2006: Single-column model intercomparison for a stably stratified atmospheric boundary layer. *Boundary-Layer Meteorol.*, **118**, 273–303.

Galperin, B., L. H. Kantha, S. Hassid, and S. Rosati, 1988: A quasi-equilibrium turbulent energy model for geophysical flows. *J. Atmos. Sci.*, **45** (1), 55–62.

Harlow, F. H. and J. E. Welch, 1965: Numerical calculation of time-dependent viscous incompressible flow of fluid with free surface. *J. Comput. Phys.*, **8**(12), 2182–2189.

Holt T. and S. Raman, 1988: A review and comparative evaluation of multilevel boundary layer parameterizations for first-order and turbulent kinetic energy closure schemes. *Rev. Geophys.*, **26** (4), 761–780.

Holtslag, A. A. M., 1998: Modelling of atmospheric boundary layers. *Clear and Cloudy Boundary Layers*, A. A. M. Holtslag and P. G. Duynkerke, Eds., North Holland Publishers, 85–110.

Hurley, P., 2007: Modeling mean and turbulence fields in the dry convective boundary layer with the eddy-diffusivity/mass-flux approach. *Boundary-Layer Meteor.*, **125**, 525–536.

Lenderink, G. and A. A. M. Holtslag, 2000: Evaluation of the kinetic energy approach for modeling turbulent fluxes in stratocumulus. *Mon. Weather Rev.*, **128**, 244–258.

Lesieur, M. and O. Metais, 1996: New trends in large-eddy simulations of turbulence. *Annu. Rev. Fluid Mech.*, **28**, 45–82.

Lilly, D. K., 1962: On the numerical simulation of buoyant convection. *Tellus*, **14**(2), 148–172.

Mellor, G. L. and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. *Rev. Geophys. Space Phys.*, **20** (4), 851–875.

Morinishi, Y., T. S. Lund, O. V. Vasilyev, and P. Moin, 1998: Fully conservative higher order finite difference schemes for incompressible flow. *J. Comput. Phys*., **143**(1), 90–124.

Nakanishi, M., 2001: Improvement of the Mellor-Yamada turbulence closure model based on large-eddy simulation data. *J. Atmos. Sci.*, **46** (14), 2311–2330.

Neggers, R. A., 2009: A dual mass flux framework for boundary layer convection. Part II: Clouds. *J. Atmos. Sci.*, **66**, 1489–1506.

Neggers, R. A. J., M. Köhler, and A. C. M. Beljaars, 2009: A Dual Mass Flux Framework for Boundary Layer Convection. Part I: Transport. *J. Atmos. Sci.*, **66**, 1465–1487.

Nieuwstadt, F. T. M., P. J. Mason, C-H. Moeng, and U. Schumann, 1992: Large-eddy simulation of the convective boundary layer: a comparison of four codes. *Turbulent Shear Flows*, **8**, 343–367.

Ogura, Y. and N. A. Phillips, 1962: Scale analysis of deep and shallow convection in the atmosphere. *J. Atmos. Sci.*, **19**, 173–179.

Randall, D. A. and Q. Shao, 1992: A second-order bulk boundary-layer model. . *J. Atmos. Sci.*, **49** (20), 1903–1923.

Schmidt, H. and U. Schumann, 1989: Coherent structure of the convective boundary layer derived from large-eddy simulations. *J. Fluid Mech.*, **200**, 511–562.

Simpson, J. and V. Wiggert, 1969: Models of precipitating cumulus towers. *Mon. Weather Rev*., **97**, 471–489.

Siebesma, A. P., P. M. M. Soares, and J. Teixeira, 2007: A combined eddy-diffusivity mass-flux approach for the convective boundary layer. *J. Atmos. Sci.*, **64**, 1230–1248.

Siebesma, A. P. and J. Teixeira, 2000: An advection-diffusion scheme for the convective boundary layer: Description and 1d-results. *Proc. 14th Symp. on Boundary Layers and Turbulence*, Aspen, CO, Amer. Meteor. Soc., 133–136.

Smagorinsky, J., 1963: General circulation experiments with the primitive equations. I. The basic experiment. *Mon. Weather Rev.*, **91**, 99–164.

Soares, P. M. M., P. M. A. Miranda, A. P. Siebesma, and J. Teixeira, 2004: An eddy-diffusivity/mass-flux parameterization for dry and shallow cumulus convection. *Q. J. R. Meteorol. Soc.*, **130**, 3365–3383.

Soares, P. M. M., P. M. A. Miranda, J. Teixeira, and A. P. Siebesma, 2007: An eddy-diffusivity/mass-flux boundary layer parameterization based on the turbulent kinetic energy equation. *Special issue on micrometeorology, Fisica de la Tierra,* **19**, 147–161.

Spalart, P. R., R. D. Moser, and M. M. Rogers, 1991: Spectral methods for the Navier–Stokes equations with one infinite and 2 periodic directions. *J. Comput. Phys.*, **96**(2), 297–324.

Stevens, B. and Coauthors, 2005: Evaluation of large-eddy simulations via observations of nocturnal marine stratocumulus. *Mon. Weather Rev*., **133**, 1443–1462.

Stevens, B. and A. Seifert, 2008: Understanding macrophysical outcomes of microphysical choices in simulations of shallow cumulus convection. *Journal of the Meteorological Society of Japan*, **86A**, 143–162.

Stull, R. B., 1988: An introduction to boundary layer meteorology. Kluwer Academic Publishers, 666 pp.

Teixeira, J. and S. Cheinet, 2004: A simple mixing length formulation for the eddy-diffusivity parameterization of dry convection. *Boundary-Layer Meteorol*., **110**, 435–453.

Vallis, G. K., 2006: Atmospheric and Oceanic Fluid Dynamics: Fundamentals and Large-Scale Circulation. Cambridge University Press.

Wensong, W. and P. A. Taylor, 2003: On modeling the one-dimensional atmospheric boundary layer. *Boundary-Layer Meteor.*, **107**, 371–400.

Witek, M. L., J. Teixeira, and G. Matheou, 2010: An integrated TKE-based eddy-diffusivity/mass-flux boundary layer closure for the dry convective boundary layer. Submitted to J. Atmos. Sci.

Wyngaard, J. C., 1992: Atmospheric turbulence. *Annu. Rev. Fluid Mech.*, **24**, 205–233.

EDMF in COAMPS 4 – extension to shallow cumulus parameterization.

The EDMF scheme described in Witek et al. (2010, in revision) is implemented in the newly released COAMPS 4 version of the model. The successful one-dimensional (1D) simulations of the convective boundary layer already performed are being currently followed by the extention of the scheme to represent shallow cumulus convection. A scheme that exploits the EDMF concept as well as a probability density function (PDF) cloud parameterization is being used. The basis for this COAMPS implementation extension is a study to develop a unified boundary layer and shallow cumulus scheme based on the EDMF parameterization. In this study, a novel eddy-diffusivity/mass-flux (EDMF) scheme for combined shallow moist convection and boundary layer turbulence in the atmosphere is developed. The originality of the present parameterization scheme is the way the condensation in the thermals, which are modeled with a mass-flux, is represented. The moist mass-flux delineates cumulus clouds. Similar to traditional schemes, the single dry mass-flux is initialized at the surface and integrated in the vertical. At each model level, the possibility of condensation (i.e. cloud formation) within the udraft is considered based on a probability density function (pdf) cloud scheme. If the mass-flux partially condenses, it is separated into a moist and a dry, which are henceforth integrated separately in respect to vertical coordinate. The procedure is repeated at the next model level whereas the moist mass-flux is allowed to dry. Accordingly, the EDMF scheme branches a single dry updraft into numerous moist and dry updrafts. With this scheme the need to define a cloud base closure for the mass-flux is avoided. The EDMF was implemented in a single column model and evaluated using LES data corresponding to a well studied Barbados Oceanographic and Meteorological Experiment. The new EDMF scheme is able to represent the properties of shallow-cumulus and the turbulent fluxes encountered in cumulus-topped boundary layers. It is shown that the scheme is not sensitive to the vertical resolution and the values of the model parameters.

IMPACT/APPLICATIONS

These results have an important potential future impact for the weather prediction capabilities of the US Navy after the implementation of these new parameterizations in the COAMPS model.

In addition it will be the first time that a unified parameterization of the marine boundary layer has ever been developed and implemented in a weather prediction model.

TRANSITIONS

The new EDMF parameterization will be proposed for a transition at FNMOC after implementation and adequate testing in the COAMPS model

RELATED PROJECTS

J. Doyle (NRL) is currently supported by an existing ONR project related to physical parameterizations and numerical techniques for high-resolution next-generation applications of COAMPS

PUBLICATIONS

- Matheou, G., D. Chung, B. Stevens, and J. Teixeira, 2010: On the fidelity of large-eddy simulation of shallow precipitating cumulus convection. *Mon. Weather Review*, in revision.

- Witek, M.L., J. Teixeira, and G. Matheou, 2010: An integrated TKE based eddy-diffusivity/mass-flux boundary layer scheme for the dry convective boundary layer. *Journal of the Atmospheric Sciences*, in revision.

- Lee, S., B. Kahn, and J. Teixeira, 2010: Characterization of Cloud Liquid Water Content Distributions from CloudSat. *Journal of Geophysical Research*, **115**, D20203, doi:10.1029/2009JD013272.

- Kawai, H., and J. Teixeira, 2010: Probability Density Functions of Liquid Water Path of Marine Boundary Layer Clouds: Geographical and Seasonal Variations and Controlling Meteorological Factors, *Journal of Climate*, **23**, 2079-2092.

- Kahn, B. H., and J. Teixeira, 2009: A global climatology of temperature and water vapor variance scaling from the Atmospheric Infrared Sounder, *Journal of Climate*, **22**, 5558–5576, doi: 10.1175/2009JCLI2934.1.